Simulating the Dynamic Responses of Highway Bridges for Multiple Vehicle Presence Effects

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Abstract

The paper investigates the dynamic amplification factors to be applied for critical loading events involving multiple vehicles in bridge design. Numerical simulation of dynamic responses of two typical highway bridges, a short span one and a medium to large span one, reported in the literature as part of the DIVINE research program was carried out for the purpose. During DIVINE field investigations, these bridges had responded very heavily to single truck passage to the extent that the current dynamic amplification factors in bridge design codes were exceeded. From the simulation studies it is observed that vehicles with air suspensions, generally supposed to induce lower dynamic loads compared to those with steel suspensions, are capable of generating amplified bridge responses whenever the combination of road profile and vehicle speed is capable of exciting the critical frequencies and there is condition of frequency matching between bridge and vehicle. Also, it was observed in the case of short span bridge that there can be many cycles of amplified bridge oscillations even when the vehicle is over the bridge, which may have implications in its fatigue life. Presence of multiple vehicles in bridge span reduced the dynamic amplification factors in case of both short span and medium span bridges, with the reduction being more pronounced near vehicle speeds capable of exciting critical vehicle frequencies. The reduction was more pronounced in the case of medium to large span bridge than for the one with short span.

Keywords: *Highway bridges, Dynamic amplification factor, Road surface roughness, Vehicle bridge interaction.*

1 Introduction

The dynamic amplification factors presented in design codes have been mainly based on studies carried out on the movement of single vehicles over the bridge deck. When the carriageway comprises multiple lanes, design codes require vehicles to be placed on all lanes in the assessment of design forces in the deck structure. In general it is tacitly assumed that the same dynamic amplification factors are applicable even under such combined loading (IRC 6: 2000). Though some western codes specify reduction factors in the event of multiple vehicles, no systematic research is seen in literature regarding the same. The present study explores the basis for reduction in dynamic amplification factors with specific reference to earlier field studies reported in the literature (DIVINE 2000).

2. Description of bridges and vehicles

Two typical bridges – a short span RC slab type bridge (Camerons Creek bridge in Australia) and a medium to long span one (Sort bridge, Switzerland) which responded the maximum to the test vehicles were selected for the current analysis. A brief summary of the main details related to the two bridges is shown in Table 1. The short span bridge with simply supported boundary conditions had a span of 9.14 m. The Sort bridge was a five span continuous bridge (36 m, 58.42 m, 69.95 m, 58.42 m and 36 m) of single cell box girder type. A review of Table 1 reveals some interesting features. Even with good pavement profile conditions, there is possibility of very high dynamic responses that too exceeding the current DAF provisions in various bridge codes. At the same time it is to be acknowledged that the reported values were the result of field investigations involving single vehicle crossing events.

Table 1: Details of bridges (DIVINE 2000)

Bridge	*Span (m)*	*Type*	*1st Freq. [Hz]*	*Damping [%]*	*Pavement condition*	*Frequency matching*	*DAF (steel susp.)*	*DAF (Air susp.)*
Sort	*70*	*5 span continuous PSC single cell box girder*	*1.62*	*1*	*A*	*body-bounce, air*	*1.1*	*1.26*
Cameron Creek	*9.14*	*4 simply supported RC slab spans*	*11.3*	*1.5*	*B*	*axle - hop (Boral vehicle)*	*2.05*	*1.75*
						axle - hop (Shell vehicle)	*...*	*2.37*

The test vehicles consisted of six axle tractor semi trailer of gross vehicle weight 425 kN and a five axle tractor semi trailer of GVW 450 kN. Details regarding axle loads and geometric features were taken from the DIVINE report (2000). As the suspension and tire characteristics of trucks used for testing was not available details of similar characteristics were taken from literature (Fu and Cebon 2002) and are presented in Table 2. The spring stiffness of the vehicle model were arrived at accordingly.

Table 2: Vehicle suspension and tyre characteristics

Parameter	*Value*
Steer axle tire stiffness	*8.75 MN/m*
Drive axle tire stiffness (Dual tire)	*1.75 MN/m*
Rear axle tire stiffness (Dual tire)	*1.75 MN/m*
Tyre damping (single tyre)	*2.00 kN-s/m*
Steer axle steel leaf suspension (9 leaf)	*0.25 kN/m*
Drive axle (tandem axle 4 spring, 14 leaf) steel suspension	*1.00 kN/m*
Rear axle (tridem) steel leaf suspension	*0.94MN/m*
Drive axle and rear axle air suspension (Iso)	*3.62 MN/m*
Steel leaf suspension damping (single)	*6.60 MN-s/m*
Air suspension damping (single) for drive axle	*17 kN-s/m*
Air suspension damping (single) for rear axle	*15 kN-s/m*

2.1 Road surface conditions

Though the pavement type was classified as Class B (ISO 1995) it was reported that the deck profile conditions were good while the approach region was somewhat deteriorated. Hence the reported classification obtained from the spectral analysis of sample profiles reflected the average conditions alone. More over it was reported that the approach portion for the northbound traffic had a short wavelength irregularity capable of exciting the axle hop vibration mode of vehicles. The profile conditions for Sort bridge was classified as of Class A.

3 Numerical models of vehicle bridge system

Since the current interest is on the bridge global responses, a 2D grillage idealization, was used for modeling short span bridge as it is widely accepted that a more complicated bridge model does not improve the accuracy level much as far as the bridge global responses are concerned (Nassif 2004). For the Sort bridge, a 1D idealization using beam finite elements was employed.

For vehicles, 2D planar models are adopted as it is reported that the roll frequencies of heavy vehicles are too low so that the dynamic loading due to this vehicle vibration mode is too low to impart any significant bridge vibrations. (Cebon 2000, Huang 2002) The schematic of the model developed and used in present study is shown in Fig.1. The model is capable of simulating truck passage involving multiple vehicles in same or two lanes. The truck configuration and speed of travel can be same or different in two lanes. A Six axle vehicle model with nine degrees of freedom will alone be employed in the current analysis.

3.1 Governing equations of motion

Grillage model of bridge, equations of which in matrix form, were formulated employing the finite element discretisation concept using grid elements. Vehicle equations of motion were developed using Lagrangian approach given by *(1)*

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}_i}\right) - \frac{\partial T}{\partial q_i} + \frac{\partial U}{\partial q_i} = Q_i \qquad (1)$$

where T and U represents the kinetic and potential energy of the vehicle system, Q_i the non conservative forces including damping and q_i representing the generalized degrees of freedom of the model.

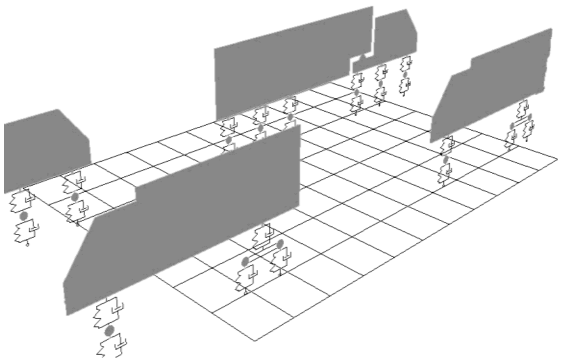


Figure 1: Schematic of developed numerical model

The bridge and vehicle equations are coupled through the contact forces acting at the bridge vehicle contact points. Typical expression for the time dependent contact force at i^{th} contact point is given in *(2)*.

$$Kt_i(Za_i(t) - w(x_i,t) - r(x_i)) + Ct_i(\dot{Z}\,a_i(t) - \dot{w}(x_i,t) - V\frac{dr(x_i)}{dx}) \qquad (2)$$

Here, Kt_i and Ct_i represent the tire stiffness and damping, Za_i represents the axle vertical displacement, $w(x_i,t)$ the bridge displacement at i^{th} wheel contact point, $r(x_i)$ the road roughness ordinate at the contact point and V the vehicle speed.

The final form of a general coupled time variant vehicle bridge interaction equations is shown in *(3).*

$$\begin{bmatrix} [M_{bb}]+[\overline{M}] & [0] \\ [0] & [M_{vv}] \end{bmatrix} \begin{Bmatrix} \{\ddot{U}_b\} \\ \{\ddot{U}_v\} \end{Bmatrix} + \begin{bmatrix} [C_{bb}] & [C_{bv}] \\ [C_{vb}] & [C_{vv}] \end{bmatrix} \begin{Bmatrix} \{\dot{U}_b\} \\ \{\dot{U}_v\} \end{Bmatrix} + \begin{bmatrix} [K_{bb}] & [K_{bv}] \\ [K_{vb}] & [K_{vv}] \end{bmatrix} \begin{Bmatrix} \{U_b\} \\ \{U_v\} \end{Bmatrix} = \begin{Bmatrix} \{f_b^{int}\} \\ \{f_v^{int}\} \end{Bmatrix} \qquad (3)$$

The subscripts 'b' and 'v' stands for bridge and vehicle respectively and $[\overline{M}]$ represents the time dependent inertial contribution from axle mass attached to bridge deck (in case of rail car models only). A program was developed in C++ for the solution of coupled equations of motion.

3.2 Road Surface profiles

Excluding the local discontinuities such as potholes or bumps from the general profile a typical road surface can be modelled as a homogenous Gaussian process with zero mean (Dodds and Robson, 1973). According to the International Standard for measurement and reporting road surface profiles (ISO 8608-1995), road surfaces have been classified in to eight from class A to H based on the increasing degree of roughness. In the present study synthetic road profiles were generated from the power spectral density definition of the same *(4)* using *(5)* (Shinozuka 1972).

$$\Phi(\Omega)=\Phi(\Omega_0)\left(\frac{\Omega}{\Omega_0}\right)^{-w} ;\ \Omega_l \le \Omega \le \Omega_u \qquad (4)$$

Here , Ω_0 being the reference spatial frequency (0.1 cycles/m), w = 2 is the exponent of fitted PSD, Ω_l and Ω_u the lower and upper cut off spatial frequencies chosen as 0.01 and 10 cycles/m respectively.

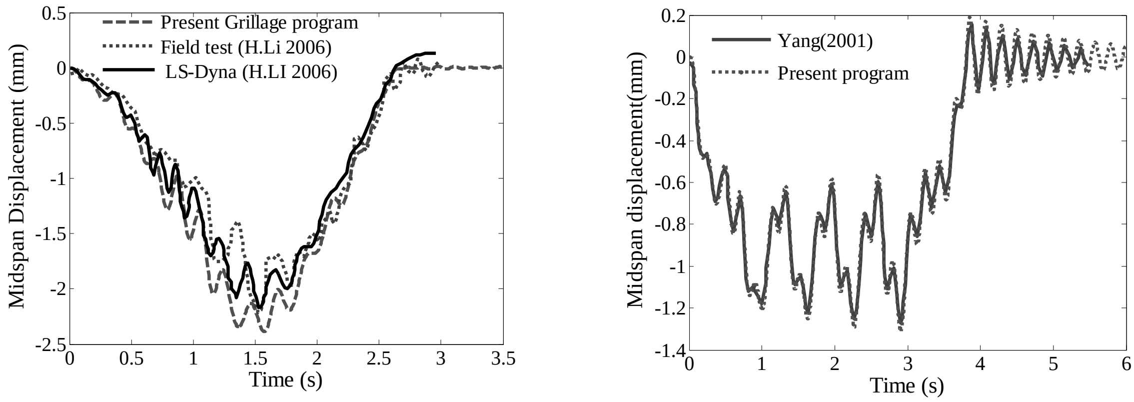
$$r(x_i)=\sum_{i=1}^{N}\sqrt{2\Phi(\Omega_i)\Delta\Omega}\cos(2\pi\Omega_i x+\theta_i) \qquad (5)$$

where θ_i is a set of random phase angles uniformly distributed in $[0, 2\pi]$

For Camerons Creek bridge, two profiles conditions were employed in the analysis – a random profile of class A type and a deterministic sinusoidal profile for the approach region of left lane alone, capable of exciting the axle hop frequencies of vehicle models (wavelength = 1.42 m). For analysis of Sort bridge a sinusoidal profile capable of exciting the vehicle bounce mode was employed (wavelength 10.86 m).

3.3 Validation of Models

Vehicle model developed was validated with results available in literature (Elmadany 1980). The algorithm and program for simulating the dynamics of bridge vehicle system was validated for two separate cases. The first one was for the case of a multiple rail car (five car) case (Yang 1999) where a beam idealization was used for bridge and second with a field test / FE simulation of highway bridge for single vehicle case (Li et.al 2006). A six degree of freedom rail car model and an eight degree of freedom five axle tractor semi trailer model developed as part of the research program were used for validations. The properties of bridges and vehicle models as reported in the respective papers were used and the results are shown in Fig.2 . It can be seen that results from the developed program matches well with the reported numerical studies and reasonably well with the reported field test results.



(a) Field test-single vehicle event.(Li et.al 2006) ***(b) multiple rail car movement (Yang et.al 2001)***

Fig.2 Validation for developed program

3.4 Frequencies of bridge and vehicle models

Linearized suspension characteristics of both steel leaf and air suspensions given in Table 2 were used for the vehicle model. The bounce frequencies of steel and air suspended vehicles came to 2 Hz and 1.53 Hz respectively. Axle hop frequencies of steel leaf suspended vehicles ranged from 12.25 to 13.5 Hz while that of air suspended vehicles were in the 11.57 to 11.74 Hz band.

Grillage model of Cameron Creek bridge yielded a first flexural frequency of 11.76 Hz while that of Sort bridge came to 1.58 Hz, both of which closely matched the one reported in literature. Also it is of interest to note that the axle hop frequencies of both vehicle models were close to the fundamental frequency of short span Cameron Creek bridge while the bounce frequency of air suspended model is close to the first vertical bending mode of Sort bridge.

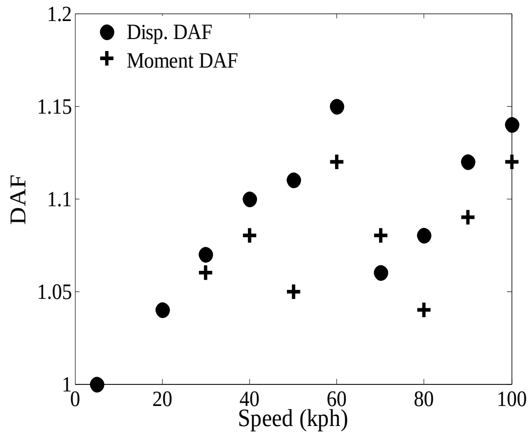
4 Simulation studies

4.1 Camerons Creek bridge (Short span)

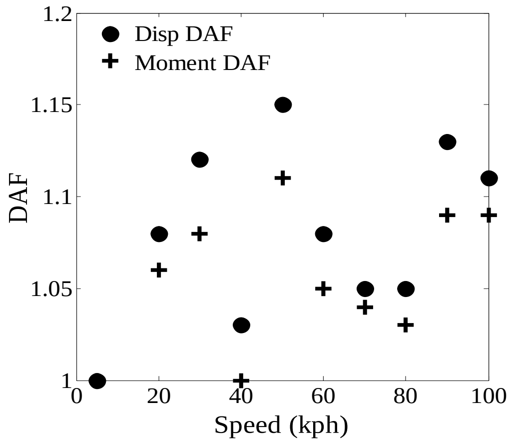
Bridge vehicle interaction analysis involving single six axle vehicle with steel leaf and air suspension type yielded similar results for various running speeds from 20 kph to 100 kph under smooth profile conditions. As the peak response amplification observed for the case were very low (less than 5%), the same has not been shown here. But from this analysis it may be concluded that the speed parameter, being widely reported in literature as the ratio of half the crossing frequency (V/2L) to the bridge fundamental frequency, is having negligible influence on the dynamic response of this bridge and the very high responses reported in field investigations may be due to the influence of road roughness alone.

4.1.1 Interaction analysis involving single vehicle loading events:

Fig.3 shows the variation of DAF with speed for the case of vehicles with steel and air suspensions, being excited by class A type road profile roughness.



(b) Vehicle model with steel suspension

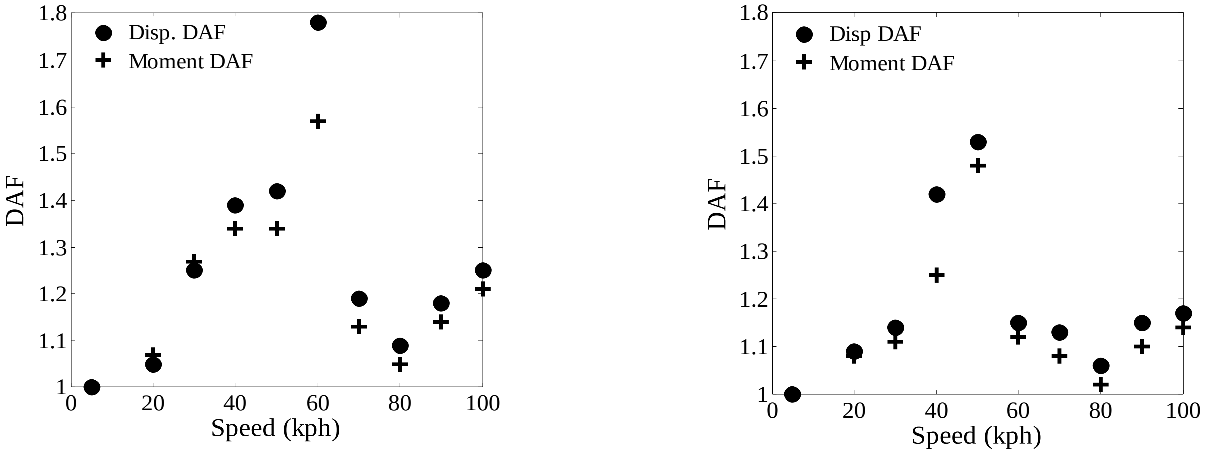


(b) Vehicle model with air suspension

Figure 3. Variation of bridge DAF with speed (class A road roughness excitation for vehicle)

It shows the occurrence of peak bridge responses especially near speeds of 50 kph for vehicle models with air suspension and 60 kph for vehicle models with steel suspension. The occurrence of peak responses at different speeds even for same road profile conditions is attributed to the slight difference in axle hop frequencies of both vehicle models. But still the peak responses were much less than the one reported in literature. A careful analysis of the DIVINE report revealed that there was a short wavelength irregularity in the approach region of left bound traffic lane of this bridge. This irregularity was included in the current analysis in the form of a simple sinusoidal function with amplitude 5 mm and wavelength 1.42 m so that the critical axle hop frequencies of vehicle models with steel and air suspensions were excited at travel speeds of 60 kph and 50 kph respectively. The results of analysis is shown in Fig 4 which clearly shows the amplified responses near the critical speeds for both vehicle models. Since the exact roughness amplitudes and vehicle properties were not available, the peak responses could not be realistically simulated but a review of report (DIVINE 2000) will show that the general trend remained the same.

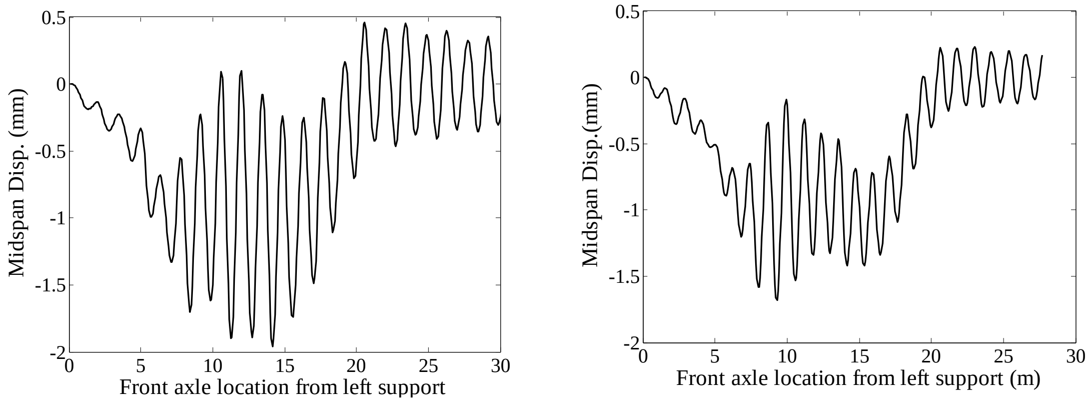
Typical time histories of bridge responses generated by the two vehicle models travelling at critical speeds is shown in Fig.5. It can be observed that there are many cycles of amplified oscillations even when the vehicle is over the bridge.



(a) Vehicle model with steel suspension

(b) Vehicle model with air suspension

Figure 4. Variation of bridge DAF with speed (axle hop excitation for vehicle)



(a) Vehicle model with steel suspension

(b) Vehicle model with air suspension

Fig 5 . Midspan bridge response history induced by two vehicle models moving at critical speed

It can be seen that the magnitude of reduction is dependent on the speed of travel and also the peak reduction is observed near the critical speeds capable of exciting the critical vehicle frequencies. Hence it may be concluded that the reduction in DAF associated with multiple vehicle events is not due to increase in static effects alone but due to the complex interaction phenomenon occurring near the critical frequencies which in turn is dependent on the mass ratio of two interacting systems. Another interesting feature observed was that at high speeds the response amplification factors from multiple presence events were higher than that observed from single vehicle events. To confirm this finding the results of a simple analysis involving a quarter car model for vehicle and simply supported beam model for bridge, previously made by the authors is shown in Fig.6. There also it is observed that the single vehicle event produced lower amplification factors at certain speeds. More studies are required to confirm this phenomenon.

Table 2: Comparison of DAF associated with single vehicle and two vehicle crossing event.

Speed (kph)	*Single vehicle crossing event*		*Two vehicle crossing event*		*% reduction in DAF associated with two vehicle*
	Displacement DAF	*Moment DAF*	*Displacement DAF*	*Moment DAF*	
20	*1.09*	*1.08*	*1.03*	*1.00*	*6*
30	*1.14*	*1.11*	*1.08*	*1.1*	*5.3*
40	*1.42*	*1.25*	*1.25*	*1.16*	*12*
50	*1.53*	*1.48*	*1.29*	*1.28*	*15.6*
60	*1.15*	*1.12*	*1.14*	*1.12*	*0.9*
70	*1.13*	*1.08*	*1.06*	*1.06*	*6.2*
80	*1.06*	*1.02*	*1.05*	*1.05*	*0.95*
90	*1.15*	*1.10*	*1.17*	*1.15*	*-1.8*
100	*1.17*	*1.14*	*1.19*	*1.17*	*-1.7*

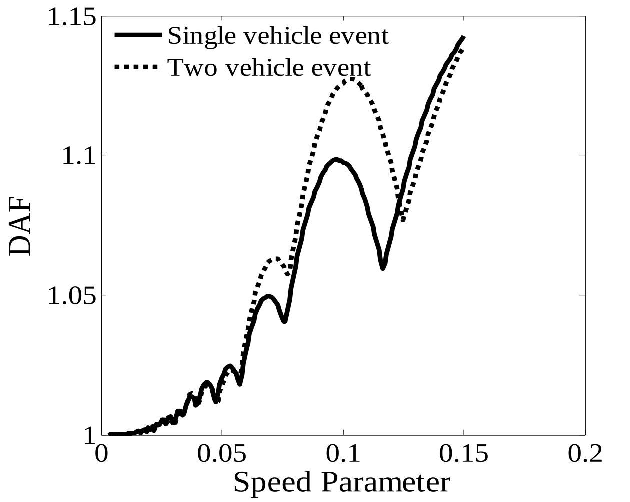


Figure 6.   Variation of DAF with speed parameter

4.2 Sort bridge (Medium to long span)

The main purpose of analysis involving this bridge was to see the magnitude of reduction in DAF associated with multiple vehicle presence. From the results presented in previous section it is clear that the maximum reduction is observed near the critical vehicle speeds and hence the results are reported corresponding to a critical speed of 60 km/hr alone. A sinusoidal profile of amplitude 10 mm and wavelength 10.82 m was employed in analysis. Time history of midspan response corresponding to critical speed of 60 km/hr is shown in Fig.7.

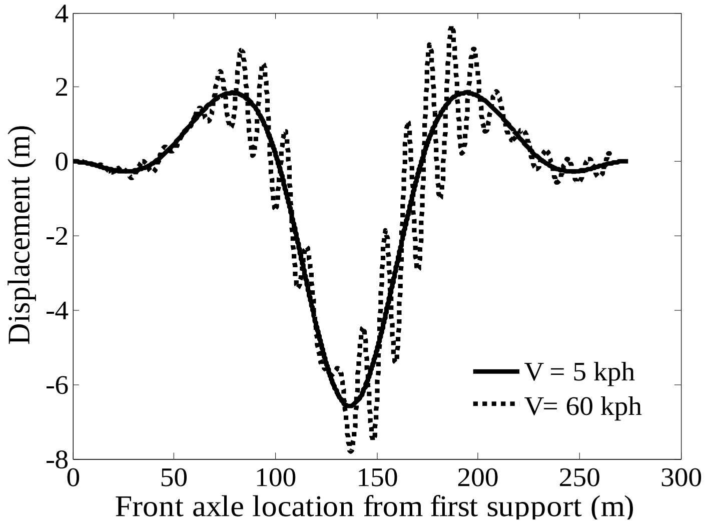


Figure 7. Typical midspan displacement history (span 3) of Sort bridge.

The DAF corresponding to single vehicle event for the critical speed came to 1.29 where as for the case of multiple vehicle event it was 1.07 (18% reduction). The preliminary results of this study on medium to long span bridge shows that considerable reduction in magnitude of DAF and hence savings in design be achieved by accounting for the influence of multiple vehicles. Such trends needs to be furthur investigated for different vehicle cofigurations, crossing speeds and profiles conditions in two lanes.

5 Conclusions

Dynamic analysis of bridge-vehicle systems involving a six axle tractor semi trailer type heavytruck and two typical bridges – a short span simply supported one and a medium to large spancontinuous bridge were carried out. The analysis involved the use of vehicle models equippedwith steel leaf suspensions as well as air suspensions. The mass distributions for the vehicle model were carefully chosen so that the critical vehicles vibration frequencies coincided wellwith those of realistic heavy trucks. General road surface characteristics similar to those observed in the field for the two selected bridges were employed in analysis. Analysis involved single vehicle crossing events as well well as simultaneous occurrence of two vehicles. Though the study couldnot exactly simulate the peak responses due to single vehicle events observed during field investigations taken up on these bridges by DIVINE, a review of the report reveals that the general trend remained almost the same. The following useful conclusions were drawn from the present study.

Very high bridge responses, mostly exceeding those being predicted using the DAF provisions in current bridge design codes, are a possibility in the event of simultaneous occurrence of two scenarios (1) critical vehicle frequencies getting excited by the combination of road profile and vehicle speed and (2) existance of a condition of critical frequency match between bridge and vehicle.

Vehicles with air suspensions, generally expected to induce low dynamic loading, too are capable of inducing amplified responses in the event of the above conditions being satisfied. But the response magnitudes may not be that high compared to those induced by steel leaf suspensions.

Short span bridges, especially with fundamental frequencies in the axle hop frequency range of heavy vehicles are most vulnerable to vehicle induced dynamic responses. For such bridges the influence of approach road conditions too will be crutial as the vehicle vibrations will not be sufficiently damped out before it reaches the bridge critical section.

It was observed in the case of short span bridge that there can be many cycles of amplified bridge oscillations even when the vehicle is over the bridge, which may have implications on its fatigue life.

Presence of multiple vehicles, except for a range of vehicle speeds, were seen to reduce the dynamic amplification factors in case of both the short span and medium span bridge included in analysis. Again, the reduction was different at different speeds, with the maximum reduction being observed near the critical speeds (capable of exciting the critical frequencies). The reduction was observed to be more with long span bridge than with the short span one. This may be attributed to the whole vehicle mass participation in coupled vibrations rather than axle group masses which often is the case with short span bridges.

Multiple presence effects investigated in current study involved similar trucks running at same speed over fully correlated road surface profiles in two lanes. Further studies are necessary to reinforce the above findings especially for cases involving multiple vehicles of different configurations travelling at different speed in same lane as well as opposing lanes with different levels of road profile conditions.

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